Low Noise Amplifiers for 140 GHz Wide-Band Cryogenic Receivers

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Abstract — We report S-parameter and noise measurements for three different InP 35 nm gate-length High Electron Mobility Transistor (HEMT) Low Noise Amplifier (LNA) designs operating in the frequency range centered on 140 GHz. When packaged in a WR-6.1 waveguide housing, the LNAs have an average measured noise figure of 3.0 dB – 3.6 dB over the 122 – 170 GHz band. One LNA was cooled to 20 K and a record low noise temperature of 46 K, or 0.64 dB noise figure, was measured at 152 GHz. These amplifiers can be used to develop receivers for instruments that operate in the 130 – 170 GHz atmospheric window, which is an important frequency band for ground-based astronomy and millimeter-wave imaging applications.

Index Terms — Astronomy, Cryogenic electronics, HEMTs, Low-noise amplifiers, MMICs, Noise measurement

I. Introduction

The atmospheric window centered around 150 GHz is an important frequency band for many astronomy measurement techniques, including radiometry, interferometry, and spectroscopy. Instruments in this frequency range, such as the ALMA telescope, are already in use, but more compact and cost-effective receiver designs are needed if larger, more sensitive arrays are going to be developed. This frequency band also has important applications in millimeter-wave imaging, including security screening and imaging from aircraft. Recent advances in High Electron Mobility Transistors (HEMTs) have improved the noise performance of Monolithic Millimeter-wave Integrated Circuit (MMIC) low noise amplifiers (LNAs) in recent years, prompting the development and testing of new MMIC receivers at higher operating frequencies [1]-[4]. These new LNAs have demonstrated noise temperatures that are competitive with existing technologies such as SIS mixers [5] and can be easily integrated into multi-chip modules that are scalable and mass-produceable [6].

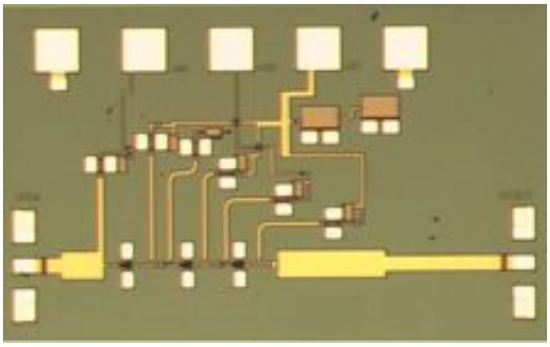

Fig. 1. Photograph of LNA 3, a 35 nm InP HEMT MMIC optimized for operation at 140 GHz.

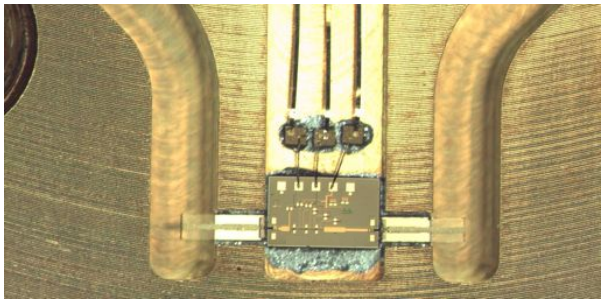

Fig. 2. Photograph of the inside of the LNA cavity housing, showing the WR-6.1 waveguide input and output, E-plane probes, LNA, and bias circuitry.

Three LNAs were tested to find the optimal design for operation in the desired 130-170 GHz frequency band. All three LNA designs are based on 35 nm InP HEMT MMIC technology. The three designs each have three stages of gain in a common-source topology, and utilize a 2-finger HEMT device with gate width of 15µm or 20µm for each finger. LNA 1 has a design optimized for operation in the frequency band centered on 180 GHz [7]-[8]. The other two LNA designs are optimized for operation at 140 GHz: one with 40 µm (LNA 2) and the other with 30 µm (LNA 3) total device peripheries. LNA 3 is pictured in Fig. 1. The LNAs were packaged in gold-plated brass blocks with WR-6.1 waveguide input and output ports, as shown in Fig. 2. We designed waveguide-to-microstrip 3 mil quartz E-plane transitions, optimized for WR-6.1 waveguide. The LNA cavity is 0.254 mm deep (10 mils) and has an open side for the DC bias circuitry. In the next sections we describe S-parameter, noise, and cryogenic noise measurements of the LNAs.

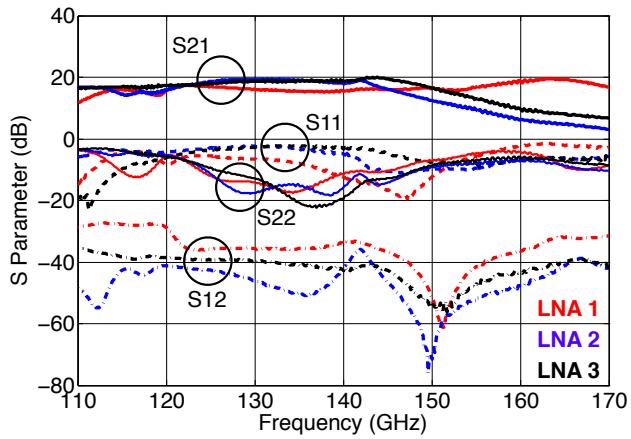

Fig. 3. Plot of the S-parameters for the three different LNA designs. The red lines are for LNA 1, the blue lines are for LNA 2, and the black lines are for LNA 3. Thick solid lines are S21, dashed lines are S11, thin solid lines are S22, and dot-dash lines are S12.

II. S-Parameter Measurements and Modeling

The S-parameters of the LNA modules were measured using WR-6 millimeter-wave extensions heads connected to a vector network analyzer and are shown in Fig. 3. The bias values were chosen so that each LNA had approximately 20 dB gain. The drain voltage for LNA 1 and LNA 2 was 0.8 V and the drain voltage was 0.5 V for LNA 3. The drain current for LNA 1 was 11 mA and the drain current for LNA 2 and LNA 3 was 12 mA. The measurements show that S11 < -1.5 dB and S22 < -3 dB for all three LNAs. LNA 1 has the greatest gain above 155 GHz.

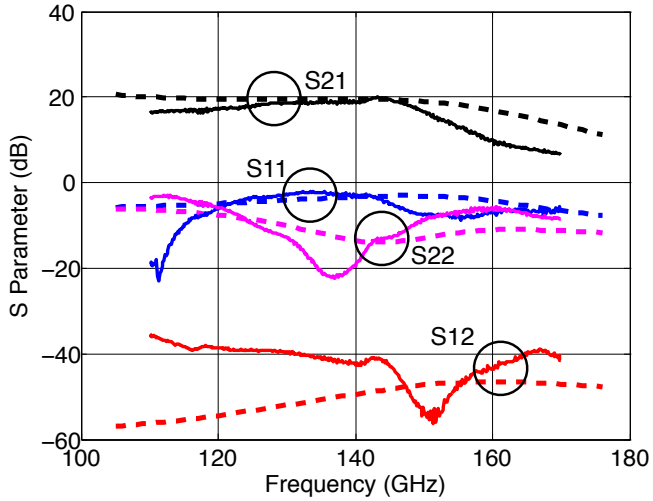

Fig. 4. Plot of the simulated (dashed lines) and measured (solid lines) S-parameters for LNA 3. There are differences between the two results because the simulation did not include the packaging that was used for the measurements.

The S-parameters for LNA 3 were modeled using Agilent's Advanced Design System software. The model results are plotted with the measured S-parameters for LNA 3 in Fig. 4 and show good agreement. The packaging for the measured LNA was not included in the model.

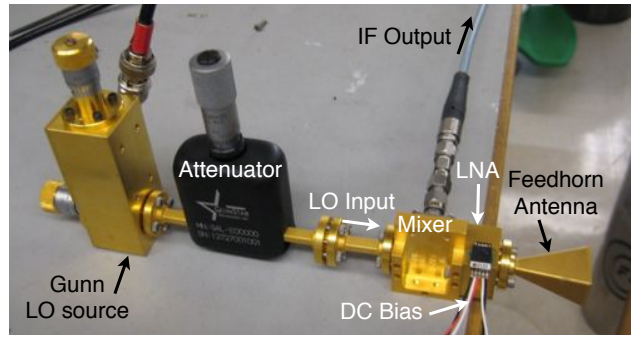

Fig. 5. Photograph of the noise temperature measurement setup at room temperature.

III. Noise Measurements at Room Temperature

The noise temperatures of the three LNAs were measured using the Y-factor method with the setup pictured in Fig. 5, which included a feedhorn antenna input and a backend second-harmonic mixer for down-conversion of the LNA output. Two local oscillator (LO) sources were used: a signal generator with a quadrupler for the frequency range from 122 – 134 GHz (61 – 67 GHz LO) and a gunn oscillator for 136 – 170 GHz (68 – 85 GHz LO). The intermediate frequency (IF) output power from the mixer was measured by a spectrum

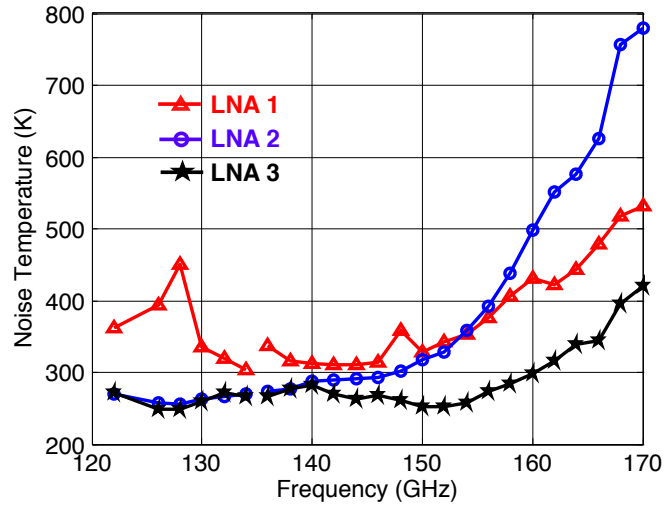

Fig. 6. Plot of the measured noise temperature for the three LNA designs. The red triangles are for LNA 1, the blue circles for LNA 2, and the black stars for LNA 3. The break in the graph between 134 and 136 GHz represents the transition from the quadrupler LO source to the gunn oscillator.

analyzer set to zero span at 500 MHz. Two different thermal loads were applied to the input in succession and the measured difference in IF output power was used to calculate the Y-factor, noise temperature, and gain. The warm load was ambient room temperature and a cone of microwave absorber drenched in liquid nitrogen provided the cold load. The LNA noise measurements were corrected for the mixer backend noise contribution, which was measured separately.

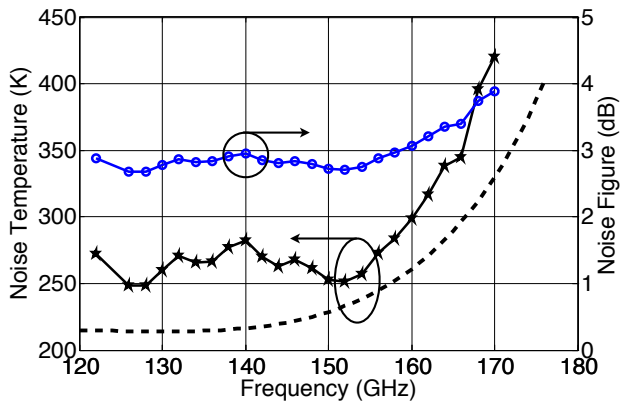

Fig. 7. Plot of the measured noise temperature (black stars) and noise figure (blue circles) of LNA 3 at room temperature. The noise temperature simulation (black dashed line) does not include the waveguide packaging or E-plane transitions.

The measured noise temperatures of the three LNAs are plotted in Fig. 6. This plot shows that the lowest spot noise measurements were 304 K at 134 GHz for LNA 1, 255 K at 128 GHz for LNA 2, and 248 K at 126 GHz for LNA 3. The average noise temperature from 122 – 170 GHz was 377 K for LNA 1, 384 K for LNA 2, and 287K for LNA 3. The average noise temperature of LNA 2 is reduced to only 312 K over the 122 – 160 GHz frequency band. The LNA gain derived from the Y-factor measurements agree with the S21 measurements for the same bias settings.

Simulated noise for LNA 3 is plotted in Fig. 7 along with the measured noise expressed as both noise temperature and noise figure. The lowest spot noise figure is 2.7 dB at 152 GHz and the average noise figure over the 122 – 170 GHz band is 3.0 dB. LNA 1 and LNA 2 have average noise figures of 3.6 dB. The measured noise of LNA 3 is greater than the simulated MMIC noise because of the additional contributions from the E-plane transitions and waveguide packaging.

IV. Cryogenic Noise Measurements

The setup for the cryogenic noise measurements, pictured in Fig. 8, was very similar to the setup for the room temperature measurements, with modifications that allowed the LNA under test to be cooled to 20 K inside a cryostat. The feedhorn antenna input was placed behind a 25.4 µm (1 mil) mylar window in the cryostat wall so that the same warm and cold loads could be used for the Y-factor measurement. LNA 1 was found to have the flattest gain over the frequency band, so it was used as a backend RF amplifier in the cryogenic noise measurements and was cooled to 20 K along with the DUT.

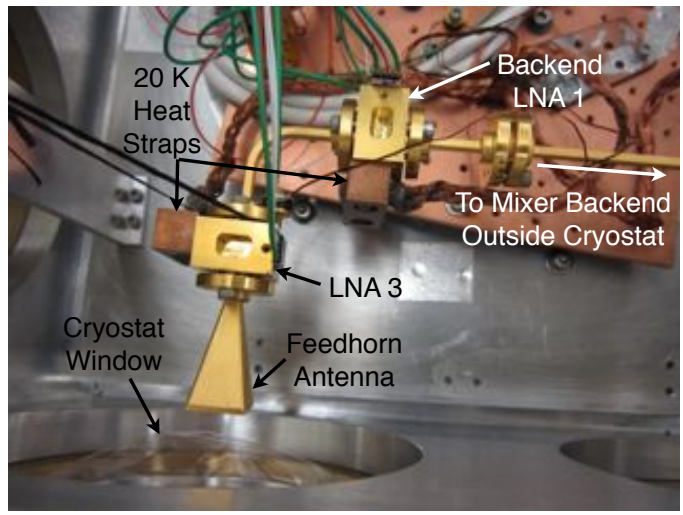

Fig. 8. Photograph of the cryogenic noise temperature measurement setup.

A piece of stainless steel waveguide was used to thermally separate the backend LNA and the cryostat wall. The mixer backend used for the room temperature measurements was located outside the cryostat. The cryogenic noise measurements were not corrected for the loss from the mylar window or backend. The mylar window loss was calculated to be approximately 0.03 dB at 140 GHz, so it is expected to add 2 K to the measured noise temperature. The backend noise is considered negligible due to the gain of the first LNA.

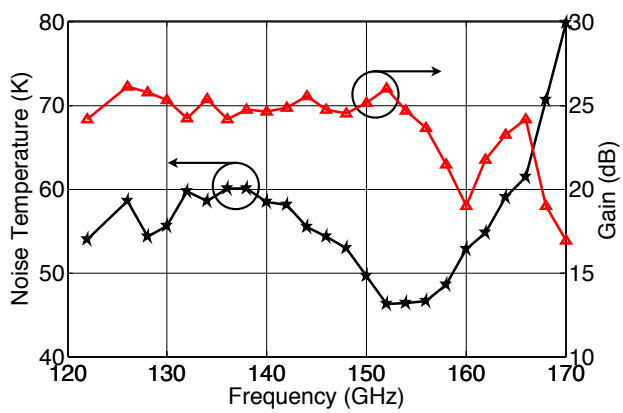

Fig. 9. Plot of the measured noise temperature (black stars) and gain (red triangles) of LNA 3 when it was cooled to 20 K. The measured noise temperature was not corrected for the noise from the other components, including the mylar window and backend LNA and mixer.

The results of the cryogenic noise measurements for LNA 3 are presented in Fig. 9. The average noise temperature was 56 K and the average noise figure was 0.77 dB over the band from 122 – 170 GHz. The lowest spot noise temperature was 46 K, or 0.64 dB in noise figure, at 152 GHz. To our knowledge, this is the lowest noise temperature measurement for a cryogenic HEMT LNA at this frequency.

V. CONCLUSION

We present S-parameter and noise measurements for three different LNA designs in the frequency range from 122 – 170 GHz. The LNAs were fabricated in a 35 nm gate length InP HEMT MMIC technology. The lowest noise temperature measurement was 248 K at room temperature and 46 K at 20 K physical temperature for LNA 3, which is a design optimized for 140 GHz with a 30 µm device periphery. These measurements show that this LNA is suitable for receivers used for astronomy and millimeter-wave imaging applications.

ACKNOWLEDGEMENT

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